A Low-Profile Cavity-Backed Dual-Polarized Spiral Antenna Array

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***Abstract*—A low profile cavity backed dual polarized printed spiral antenna array is presented. This spiral array is composed of 4 center-fed Archimedean spiral antennas printed on FR4 substrate backed by a low profile cavity without absorbing material. The dual polarization is generated using mono polarized spirals in an alternating configuration RHCP and LHCP. These spirals are connected allowing to the current to flow from the excited spirals arms into the arms of the neighboring ones. The proposed spiral array provides unidirectional beam while being dual polarized (LHCP or RHCP) for a wide bandwidth. The dual polarization of the proposed spiral array is extended to low frequencies and the gain varies up to 13dBi in the antenna bandwidth. The antenna array performances are presented and validated using electromagnetic simulations and radiation pattern measurements.**

***Index Terms*—printed spiral antenna, circular polarization, wideband antenna array, cavity backed spiral antenna**

I. Introduction

THE ARCHIMEDEAN two-arm spiral antenna is known as a frequency independent antenna [1]. This antenna is broadband and circularly polarized (CP) and its working principle is governed by simple rules. The spiral antenna minimum working frequency (VSWR<2) is directly related to the antenna diameter [2] and the spiral polarization depends on the direction of the spiral winds (clockwise or counter clockwise direction).

For these reasons the use of the spiral antenna as an array elementary structure is a promising idea for wideband dual polarized antenna array design. Indeed, in [3], authors have presented a technique based on the connection of adjacent spiral antennas to design a phased antenna array. This technique allows the antenna array to decrease the lowest operating frequency 1.8 times lower than the lowest operating frequency of an isolated spiral. The key point addressed in [3] is that the geometric characteristics of the connection are correlated with the antenna array performances. Nevertheless, no experimental validation has been provided and the concrete construction of the phased array excitation is not addressed.

In the present letter we bring a complementary experimental analysis of the work presented in [3]. Therefore, we present the results of a wide band printed antenna array constructed by simply connecting four Archimedean self-complementary spiral antennas. The spirals are printed over FR4 substrate contrarily to the spirals presented in [3] that are located in free space. We choose in this letter to connect the spirals using simple curved connections as presented in Fig. 4. In this letter, we present the spiral array performances when it is backed by a low profile rectangular cavity that gives a unidirectional beam with significant gain all over the bandwidth. The proposed antenna array is circularly polarized, allows RHCP and LHCP and a realized gain up to 13dBi. The results presented here are confirmed by a comparison between simulation and measurement data.

This letter is organized as follows. Section II describes the behavior of elementary center-fed two-arm Archimedean spiral antenna and a comparison between the performances of a printed spiral over FR4 substrate and a spiral placed in free space. The antenna array is constructed using the printed one. Results of simulation and measurement data are depicted and the antenna array performances are discussed in Section III. The cavity backed antenna array characterization is presented in Section IV. Finally, concluding remarks summarizing the antenna array performances are outlined in Section V.

II. Elementary spiral feeding system

The elementary spiral antenna used in the array construction is shown in Fig. 1. This 4.75 turns two-arm self-complementary Archimedean spiral has a diameter of 80 mm and is printed over FR4 substrate (ϵ_r=4.2) of thickness 0.8mm. Based on [4], the input impedance Z_{in} of spiral antenna printed over a substrate with relative permittivity ϵ_r is calculated using:

$$Z_{in} = \frac{Z_{free\,space}}{\sqrt{\varepsilon_{eff}}}, \qquad (1),$$

where $Z_{free\quad space}$ corresponds to the input impedance of the spiral antenna placed in free space (188Ω for self-complementary spiral) and $\epsilon_{eff}=(1+\epsilon_r)/2$ represents the effective permittivity. Using Eq. 1, the FR4 substrate allows us to transform the self-complementary spiral input impedance to a lower value 116.6Ω.

The spiral antenna excitation is made of two RG-10 coaxial cables soldered together. The inner conductor of each cable is connected to the spiral arms (Fig. 1). Consequently, the excitation impedance applied to the antenna is 100Ω. The two

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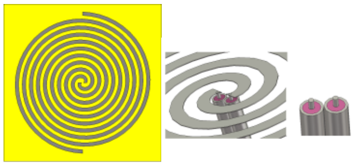

Fig. 1. Elementary spiral antenna and its feeding system

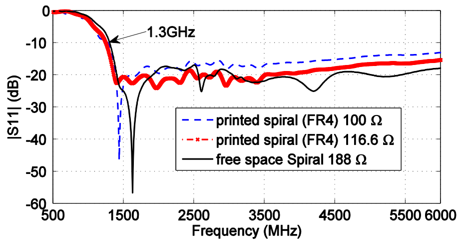

Fig. 2. Calculated reflection coefficient (S11) of elementary spiral

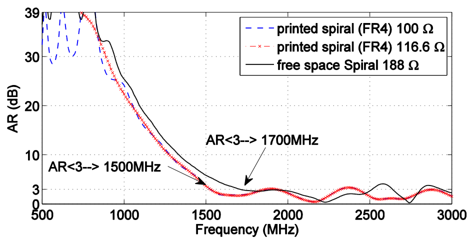

Fig. 3. Calculated Axial Ratio (AR) of elementary spiral antenna

opposed-phase signals associated to each coaxial cable are generated using a 180° hybrid coupler. This excitation technique can be generalized to any symmetrical structure with an input impedance around 100Ω. Using the electromagnetic simulation software CST Microwave Studio [5] we calculate the printed spiral antenna reflection coefficient (S11) and axial ratio (AR) as a function of the frequency when it is excited using the feeding system presented above (Fig. 1). The simulation results of the spiral printed over FR4 (100Ω) are compared with the spiral placed in free space (188Ω) and a printed spiral excited with 116.6Ω generator.

As it can be seen from Fig. 2 and Fig. 3, the printed spiral input impedance is matched to 100Ω for frequencies greater than 1.3 GHz. Considering an input port impedance equal to 116.6Ω gives the same minimum frequencies corresponding to S11<-10dB and AR<3dB (frequency>1.5GHz).

The spiral placed in a free space presents AR<3dB for frequencies greater than 1.7GHz as it is presented in Fig. 3.

In this letter, we focus on the spiral antenna performances in the lower part of the bandwidth [0.5GHz, 3GHz]. Our objective is to reach lower frequencies by connecting spirals. This is the construction principle of our antenna array. Since we are interested in a dual polarized structure with a S11<-10dB and an axial ratio AR<3dB, our frequency bandwidth is defined when both conditions are met simultaneously.

III. The Antenna Array Construction

The dual polarized array we propose here is constructed using four spiral antennas (self-complementary Archimedean spirals) separated by a distance of 82 mm which is approximately equal to the spiral external diameter (80mm). These spiral antennas are printed in FR4 substrate of thickness

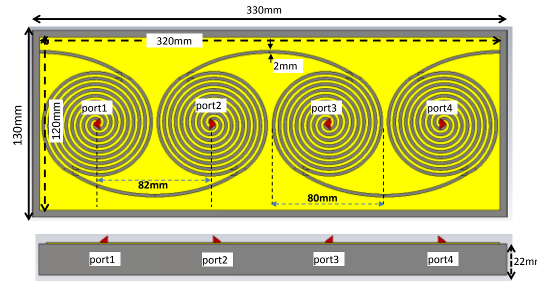

Fig. 4. (up) The antenna array considered for our investigations. The micro-strip line width is 2mm, the distance between spirals is 82mm and the FR4 substrate thickness is 0.8mm. (down) The cavity is placed at 22mm from the bottom of the array.

Fig. 5. The antenna array and the used feeding circuit composed of two pulse lab PSPL BALUN and a power divider in the middle of the photography.

0.8mm. We construct the dual polarized array by alternating right hand and left hand circularly polarized spiral as shown in Fig. 4 (Right, Left, Right, Left). The idea is to construct the array by adding curved connections between neighboring spirals. Only left hand circularly polarized spirals are excited (port2 and port4) to generate LHCP antenna array and symmetrically only right hand spirals are excited to generate RHCP antenna array.

In this letter, curved connections are used without any optimization process to connect spiral antennas. The simulation and experimental results are presented to show the effectiveness of these curved connections in building circularly polarized array.

In order to show the viability of the proposed method we compare the S11, the axial ratio and the realized gain of four structures described in Fig. 6. We aim at comparing the performances of the technique based on connecting spirals to decrease the minimum operating frequency beside the classical methods using inductive, resistive or capacitive loads [6][7].

The results presented in Fig. 7, Fig. 8 and Fig. 9 are issued from the simulation software CST Microwave Studio and only left hand circularly polarized spirals are excited (port2 and port4) for connected and disconnected spirals.

From Fig. 7, we see that connecting spirals helps to reach lower frequencies. The S11<-10dB corresponds to frequencies greater than 0.75GHz (1.3GHz for a simple spiral). From Fig. 7 and Fig. 8, we see that the coexistence of multiple spirals (disconnected) printed over the same dielectric substrate (FR4 with 0.8mm thickness) have a moderate effect over the S11 for frequencies greater than 1.3GHz. The AR of disconnected spirals is less than 3dB for frequencies greater than 1.66GHz except 1.96GHz and 2.38GHz in which we have AR>3.

When the resistive loads are placed at the disconnected spiral extremities (blue points in Fig. 6) the S11 is enhanced for frequencies smaller than 1.3GHz and the AR is less than 3dB for frequencies greater than 1.45GHz. The resistive loads

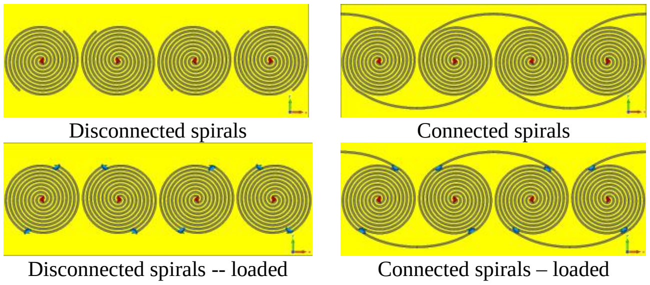

Fig. 6. The four considered configurations, the loaded spirals (down) are modeled by resistive loads placed at the spiral arm ends (blue points).

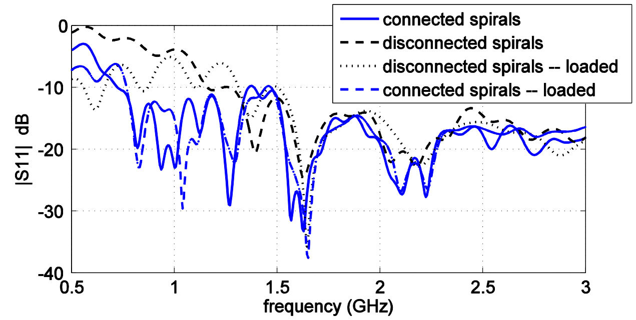

Fig. 7. The reflection coefficient presented as a function of the frequency for the different configurations described in Fig. 6.

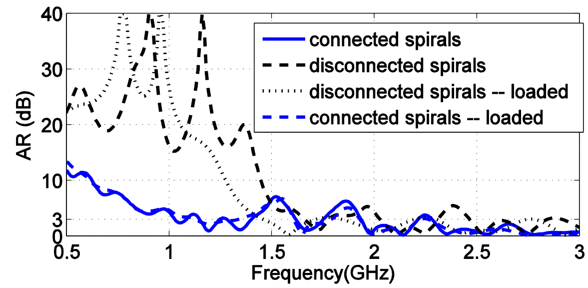

Fig. 8. The Axial Ratio presented as a function of the frequency for the different antenna configurations (Fig. 6).

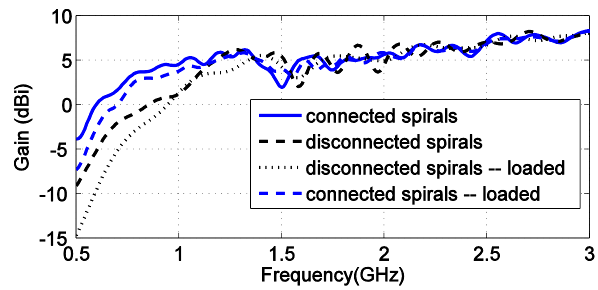

Fig. 9. The realized gain presented as a function of the frequency for the different antenna configurations (Fig. 6).

attenuate the reflected current occurring at the end of the spiral arms and the structure shows the characteristics of completely independent spirals (the same AR).

The most important result is noticed for the S11, the AR and the realized gain of connected spirals presented in Fig. 7, Fig. 8 and Fig. 9. The connected spiral array exhibits a complementary frequency band [0.85GHz, 1.45GHz] where the AR is less than 5dBi and a positive gain which values are between minimum and maximum values of 3.22dBi and 6.22dBi respectively. In addition, the AR of higher frequencies (frequency>1.9GHz) is beyond the AR of disconnected spirals.

When considering loaded spirals we mean spirals with resistive loads R equal to 200Ω. For this study, we have used different values of R and we noticed that the value of R has a minor effect on antenna performances. This is due to the fact that we use a single load (not distributed) contrarily to [8]. The resistive loads reduce the efficiency and the realized gain of the connected spiral array. Nevertheless, no great effects on the AR are noticed as shown in Fig. 8.

The regular peaks occurring at 1.52GHz, 1.86GHz and 2.2GHz, (Δf=340MHz) noticed in the connected spirals AR graph are caused by resonance phenomena due to high amplitude standing wave along the spiral arms. Authors of [9] have predicted the appearance of resonance phenomena when the spiral arms are multiples of half a wavelength.

We can conclude that connecting spirals helps to reach lower frequencies (frequencies<1.3GHz) where S11<-10dB, the AR is less than 5dB and a positive gain is guaranteed. In the next paragraph we will present the behavior of the presented configurations (Fig. 6) when backed by a low profile cavity.

IV. Cavity Backing and Measurement Results

In order to give the antenna array unidirectional beam with significant gain all over the bandwidth, we have used a 330x130x22 mm^3 rectangular low profile metallic cavity (Fig. 4). It is interesting to note that the cavity depth 22mm corresponds to λ/10 at 1.3GHz and no absorbing materials are used in the cavity contrarily to the usually presented papers dealing with cavity backed spiral antennas [10].

In Fig. 10 the S11 of different spiral array configurations are presented when backed with the low profile cavity described in Fig. 4.

The cavity is responsible of the oscillation seen in the S11 graph presented in Fig. 10. Compared with the S11 results presented in Fig. 7, the connected spiral array still have a large frequency band where S11<-10dB except for the frequencies 1.46GHz and 1.71GHz. The use of resistive loads degrades the connected spiral antenna array efficiency. However it helps to keep the S11<-10dB for frequency>0.75GHz. Let recall that the single spiral verify S11<-10 for frequencies greater than 1.3GHz.

The antenna array presented in Fig. 4 is built and fed using the feeding system presented in Fig. 5. For each excited port (port2 and port4) we use two coaxial cables soldered together and connected to a PSPL 5310A phase matched BalUn [11] to generate two opposed-phases.

We measure the radiation pattern of the cavity backed antenna array in SUPELEC anechoic chamber in the frequency band [0.6GHz, 3GHz] to characterize the radiation far field pattern over a sphere surrounding the antenna. Then, using tangential components of the measured far-field E_θ and E_φ we calculate the axial ratio (AR) and the realized gain of the antenna array in the boresight direction and compare it with the AR and realized gain calculated using CST Microwave Studio. As seen in Fig. 11 and Fig. 12, good behavior

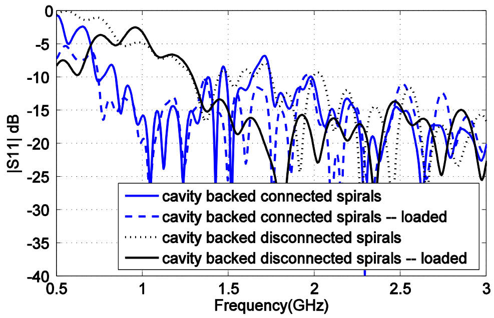

Fig. 10 The reflection coefficient presented as a function of the frequency for the different cavity backed antenna configurations (Fig. 6).

agreements are noticed between simulations and measurements results. The discrepancies are principally due to the fabrication tolerance of the constructed antenna array. As presented in Fig. 11, the AR of the cavity backed loaded connected spiral array is less than 3dB for frequencies greater than 0.76GHz except for the frequencies 1.48GHz, 1.72GHz, 1.93GHz and 2.13GHz. This is due to a combination effect of the resonance phenomena (connection between spirals) and the cavity modes. From Fig. 12, we can see that the realized gain varies for the cavity backed loaded connected spiral array between the minimum value of 0.75dBi at 0.76GHz and the maximum value of 13dBi at the frequency and 2.6GHz. The realized gain is also correlated with the cavity depth (effect over the S11).

Comparing the AR presented in Fig. 8 and Fig. 11, the observed regular peaks (Δf≈0.2GHz) for the disconnected spirals AR at the frequencies between 1.38GHz and 2.67GHz are directly linked to the cavity modes [1.36, 1.46, 1.78, 1.81, 2.27, 2.72]GHz. Also, the peaks observed at the frequencies 1.58GHz and 1.73GHz in the cavity backed connected spirals AR graph are associated to the cavity modes. However, the peak at 1.46GHz is linked to the connection between spirals. We have experienced a spiral array with longer connections (distance between spirals) and we have noticed a translation of this peak to a lower frequency.

The cavity backed printed spirals are coupled by surface wave even for non-connected spirals. When the spirals are attached together, the currents traveling from a spiral to a neighboring one are combined with surface wave on the substrate and radiate through the array connections parts producing non-circular polarized radiation pattern. Using resistive loads the parasitic radiation issued from the connection between spirals is reduced.

V. Conclusion

A low profile wide band cavity backed dual polarized spiral array (RHCP and LHCP) of printed connected spiral antennas has been presented. This antenna array is composed of four spiral antennas simply connected together in order to achieve a dual polarized array and to decrease the operating frequency (0.75GHz for the AR) lower than the elementary spiral antenna operating frequency (1.5GHz for the AR). Electromagnetic simulations and measurements have shown the efficiency of the feeding technique. A low profile cavity has been used to

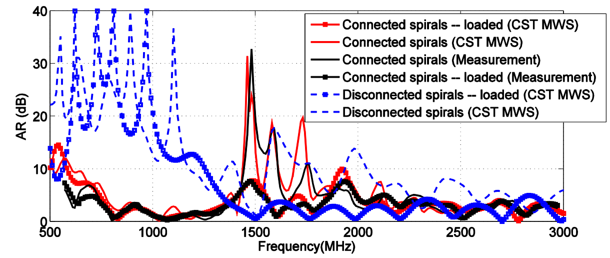

Fig. 11. The Axial Ratio (AR) presented as a function of the frequency for the different cavity backed antenna configurations (Fig. 6).

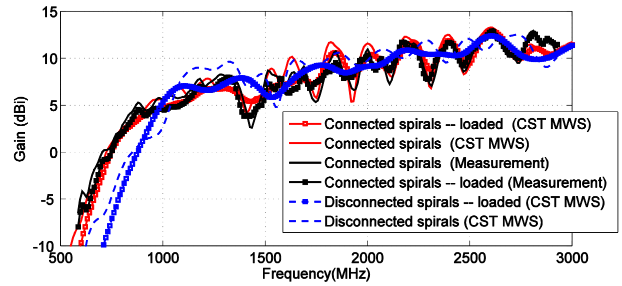

Fig. 12. The realized gain presented as a function of the frequency for the different cavity backed antenna configurations (Fig. 6).

make the antenna radiation pattern unidirectional with a realized gain up to 13dBi, where no absorbing materials are used in the cavity. The connections between antennas interact with the cavity at some single frequencies (cavity modes) degrading the AR, nevertheless, the added resistive loads help to reduce these interactions. It must be highlighted that this work has focused on simple standard Archimedean spirals but the connections can be used with any other spirals.

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